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Supporting Battle Management Command and Control: Designing Innovative Interfaces and Selecting Skilled Operators

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FOR THE DIRECTOR

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As future combat force structures, doctrine, and tactics change with the introduction of new technologies, Battle Management Command and Control (BMC2) must be being designed to be capable of flexible response to unpredictable and unconventional adversarial postures. The operators of BMC2 systems must also be appropriately selected and trained for implementing such flexibility.

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Introduction

    As future combat force structures, doctrine, and tactics change with the introduction of new technologies, Battle Management Command and Control (BMC^2) must be being designed to be capable of flexible response to unpredictable and unconventional adversarial postures. The operators of BMC^2 systems must also be appropriately selected and trained for implementing such flexibility. In this report we describe studies that attempt to meet both these objectives.

    Among the new technologies that are being rapidly deployed in BMC^2 are unmanned vehicles (UVs). The expectation is that these new technologies will provide a tactical advantage against conventional and unconventional warfare (Carafano & Gudgel, 2007). The prevailing view in the robotics community is that increased autonomy will enable UVs to function with little or no human intervention. The level of autonomy will vary depending on the size and function of the platform. By 2015, the Pentagon's goal is to replace one-third of its vehicles and weapons systems with robots and other types of UVs.

The Need for Automation

    It is likely that for the near future the goal of "full autonomy" will not be achieved and most of the contemplated systems will require either active human control or at a minimum supervision with the possibility of intervention (Barnes, Parasuraman, & Cosenzo, 2006). The human operators of these systems will thus be involved in supervisory control. Because of the likely increase in the cognitive workload demands on the human operator, automation will be needed to support timely decision making. As an example, consider sensor fusion systems and automated decision aids. These may allow tactical decisions to be made very rapidly, thereby shortening the "sensor-to-shooter" loop (Adams, 2001; Rovira, McGarry, & Parasuraman, 2007).

Automation support will also be mandated because of the high cognitive workload involved in supervising multiple unmanned air combat vehicles (Parasuraman, Cosenzo, & Barnes, 2007). An example in which cognitive workload associated with supervising tactical Tomahawk missiles is mediated through automation is described by, Cummings and Guerlain, 2007.

While automation can support a human operator in a multi-task environment, it also changes the nature of the cognitive demands on the operator (Parasuraman & Riley, 1997). Furthermore, while automated systems can enhance system performance, if poorly designed they can also lead to new performance difficulties. This is primarily due to problems in their use by human operators or to unanticipated interactions with other sub-systems. Automation issues that need to be addressed include unbalanced mental workload, reduced situation awareness (SA), decision biases, mistrust, over-reliance, and complacency (Billings, 1997; Parasuraman & Riley, 1997; Sarter, Woods, & Billings, 1997; Sheridan & Parasuraman, 2006). Thus, while automation may yield significant benefits, poorly-designed and implemented automated systems can lead to new performance costs.

Adaptive Automation

Adaptive automation has been proposed as an approach to automation that may preserve the benefits of automation while minimizing some of these performance costs (Parasuraman, Bahri, Deaton, Morrison, & Barnes, 1992). In adaptive systems the "division of labor" between human and machine agents is not fixed, but dynamic. Adaptation can be triggered by a measurement process that represents the current state of the task environment or of the operator, or by a combination of both task and operator assessment. In general, four types of invocation have been examined. (1) In the critical-events method, automation is invoked only when certain

tactical environmental events occur. This method is tied to current tactics and doctrine during mission planning. (2) In the operator performance measurement method operator mental states (e.g., mental workload, or more ambitiously, operator intentions) are inferred from performance or other behavioral measures. Because performance measures can be sparse in many modern semi-automated systems, whereas physiological measures of operator state can be obtained more frequently, operator physiological assessment provides another method for adaptive automation (Byrne & Parasuraman, 1996). In this method behavioral and/or physiological measures are used as inputs for the adaptive logic. (3) In the human operator modeling method the operator states and performance are modeled theoretically and the adaptive algorithm is driven by the model parameters. (4) Finally, the hybrid method combines one or more of these different invocation techniques (e.g., critical events and operator performance), so that the relative merits of each method can be maximized in order to minimize operator workload and minimize performance.

The adaptive automation concept was proposed over several years ago (Rouse, 1977), but empirical studies are more recent (for reviews see Inagaki, 2003; Parasuraman, 2000; Scerbo, 2001) and prototype systems have only recently been developed. One example is the Rotorcraft Pilot's Associate (RPA), which aids helicopter pilots in an adaptive manner depending on mission context and which has successfully passed in-flight tests (Dornheim, 1999). There has also been a significant amount of empirical work aimed at examining the effects of adaptive automation on human and system performance in different application domains. Automation design effectiveness is evaluated by looking at its effect on human performance, mental workload, and SA (Parasuraman et al., 2000). For example, Hilburn, Jorna, Byrne, and Parasuraman (1997) examined the effects of adaptive automation (i.e., critical event based automation) on the performance of military air traffic controllers. Controllers were provided with

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a decision aid for determining optimal descent trajectories of aircraft using (Descent Advisor (DA)), which was triggered by level of air traffic load. Hilburn et al. found significant benefits for controller workload when the DA was provided adaptively during high traffic loads, compared to when it was static or at low traffic loads.

Adaptable Automation: Delegation Interfaces—Theory and Prototypes

As these and other studies show, the performance benefits of adaptive compared to static automation is now well documented (Parasuraman et al., 2000). However, if adaptation is executed without user approval or knowledge, the cost of system unpredictability may outweigh the benefit that automation provides. At the other extreme, requiring operators to task automation at all times can increase operator workload. What is needed is a method that allows operators to explicitly task automation at times of their choosing—that is, where the user has flexibility in the use of automation and of the times of adaptation. We have recently proposed a theory of such adaptable human-automation interaction based on the concept of *delegation* (Miller & Parasuraman, 2007).

<u>Theory of Delegation Interfaces</u>

The key idea behind delegation is that the supervisor has flexibility in the use of automated support in supervising multiple UVs or other automated tools. The operator can delegate bigger, coarser-grained tasks or smaller, more precise ones with more or less explicit instruction about their performance, depending on context and task demands. Delegation architectures seek to provide highly flexible methods for the human supervisor to declare goals and provide instructions and thereby choose how much or how little autonomy to give to automation, depending on context and the current situation. It is important to note that the communication

between human and automated agents, while using a mutually understood "language", are nevertheless constrained by the specific doctrine, jargon, and tactics of the domain, and do not involve completely unconstrained communication as between two humans. Delegation is consistent with Sheridan's (1987) concept of real-time supervisory control, but seeks to provide a mechanism for human/machine delegation interactions which is richer and more flexible than has traditionally been the case in human/machine supervisory control systems. Delegation architectures provide highly flexible methods for the human supervisor to declare goals and provide instructions and thereby choose how much or how little autonomy to give to automation on an instance-by-instance basis (Parasuraman & Miller, 2006).

Our design concept for delegation interfaces allows for flexible operator response in BMC^2 systems. In this approach, human operators task automated systems at different functional levels in response to changing contexts. We extended this analysis to the problem of a team of operators supervising a large number of unmanned air vehicles (UAVs) and unmanned combat air vehicles (UCAVs). Prototypes of such delegation interfaces have also been developed for use by a single operator. We describe the approach first before describing the prototypes.

Three parameters of the human-machine system are important in designing delegation interfaces. The first is the *competency* of the system, or its ability to achieve correct behavior in context. A system is more competent whenever it provides correct behaviors more frequently or in a greater number of contexts. A second important parameter is the *workload* associated with the human operator's use of the delegation interface. The third parameter is the *unpredictability* of the system to the operator, which refers to the inability of the human to know exactly what the automation will do when. Unpredictability is a consequence of the human not personally taking all actions in the system—of not being "in control" directly and immediately. Expending

workload (especially mental workload) to monitor and understand a system reduces its unpredictability to the user, hence unpredictability is generally inversely correlated with workload and with those specific aspects of situation awareness which pertain to the understanding of the automation behaviors and the system functions they control. Good system and interface design, including improved feedback to the user about automation states and behaviors (Parasuraman et al., 2000), as well as other options such as increased reporting requirements and good hiring and training practices, can serve to reduce unpredictability. However, in general, any form of task delegation—whether to automation or other humans—must necessarily result in a degree of unpredictability if it offloads tasks (and does not replace their workload with other tasks—including monitoring and managing the offloaded tasks).

These three parameters define a tradeoff space within which a given level of competency can be achieved through some mix of workload and unpredictability. A user may reduce workload by allocating some functions to automation, but only at the expense of increased unpredictability (at least with regards to those functions); conversely, reducing unpredictability by having the user perform functions increases workload. Alternate designs for a level of competency represent different mixes of workload and unpredictability. It is sometimes possible to reduce both workload and unpredictability for a given level of competency through better design. It is also, ironically, entirely possible to increase both workload and unpredictability without achieving increased competency, which may be a feature of some current UAVs.

Prototypes

A protoype delegation interface was designed for the purpose of enabling ground-based, pre-flight mission planning for UAVs. With this interface (shown in Figure 1), the user can call a high-level "play," which corresponded to a single mission type (e.g., Airfield Denial), but also

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has extensive capability to stipulate the method and procedure for doing Airfield Denial by filling in specific variable values (i.e., which specific airfield was to be attacked, what UAVs were to be used, where they should rendezvous, etc.) and by stipulating which sub-methods and optional task path branches would be used and which would not (e.g., whether or not this instance of Airfield Denial would include an optional "Suppress Defenses" sub-task). Several user interaction styles are supported by the delegation interface, with each referencing and being integrated with the central task model. The top portion of this interface consists of a window that allows detailed navigation and visualization of the play's task structure—conveying both sequential (via left-to-right and parallel) and functional (via hierarchical drill down) relationships of tasks—called a Task Decomposition View. Such an interface supports detailed interactions with the task structures of the play and allows the user to visualize and/or constrain those structures. Here, the user directly manipulates tasks by asserting which ones are to be included and which avoided.

Another prototype involves controlling the actions of ground robots in a building clearing and mapping mission (see Figure 2). This domain has only a few plays, but the delegation interface nevertheless still permits the operator flexibility in supervision. The primary play-relevant components for this interface are shown in the upper left hand corner in Figure 2, indicating a simple, relatively "flat" tree structure of alternate deployment and surveillance plays organized by mission phase. Given the time pressure imposed in these operations, the user typically does not have the ability to "drill down" and impose more specific instructions about exactly how a "Group Deploy" task is to be performed. Instead, users simply activate general behaviors for the entire team of robots on a single-action basis. Hence, the building map and video are more important and expected to be given substantially more space during typical use.

Additional interactions and visualizations are possible—including direct, waypoint instructions to individual robots and navigation through their resulting video images—through additional popup windows.
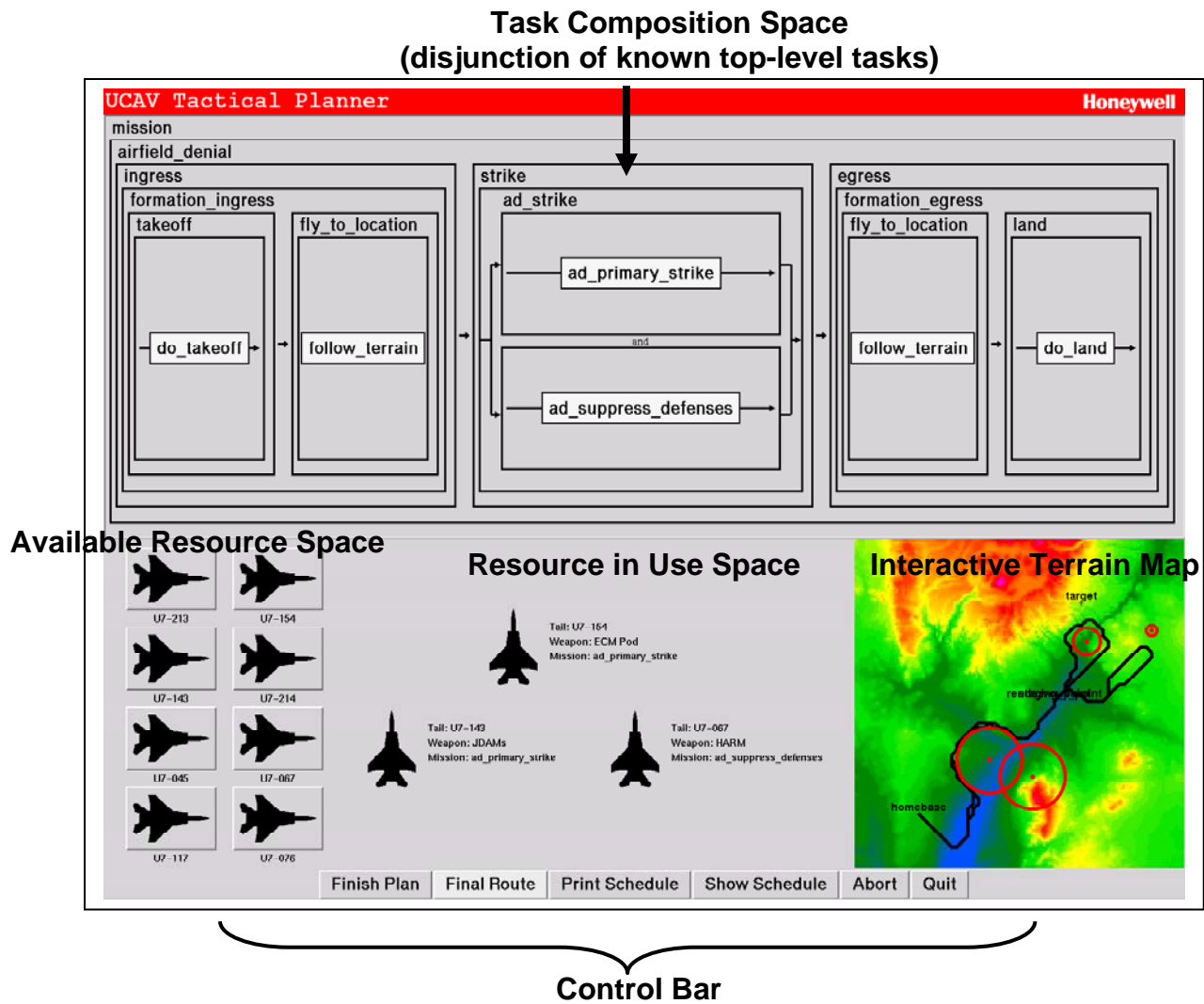

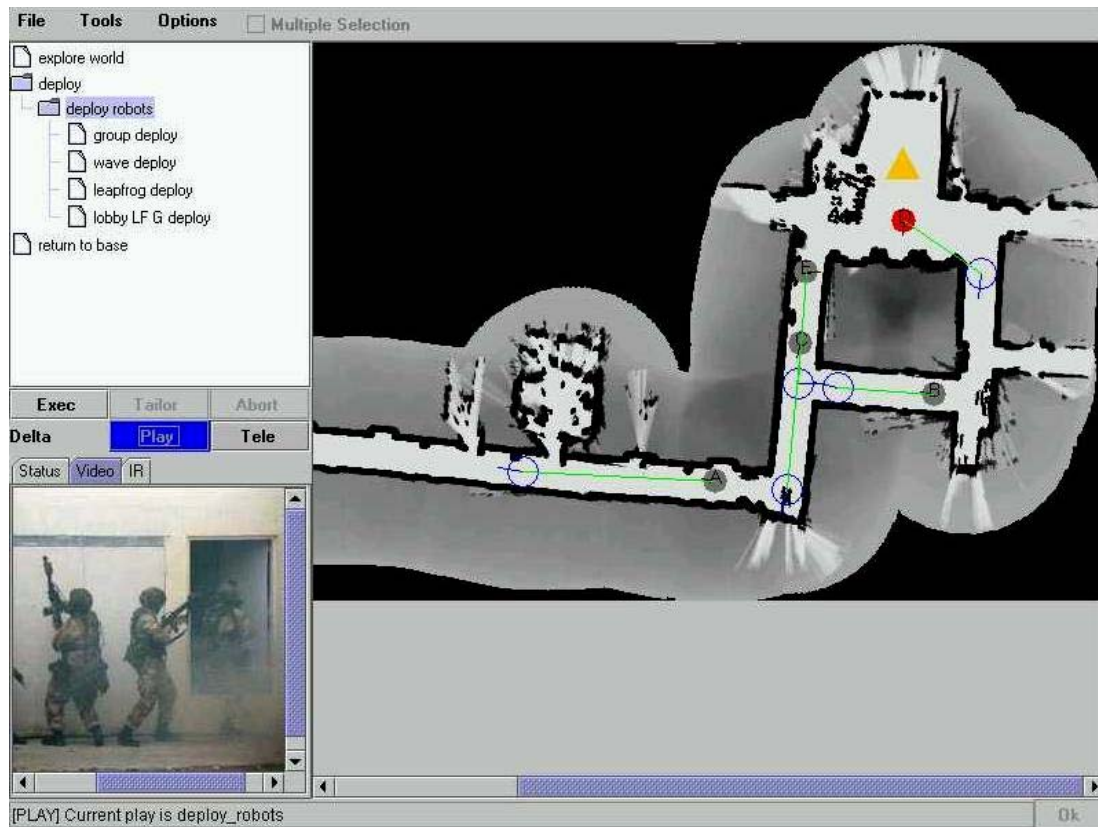Figure 1. A delegation interface for ground-based UAV mission planning.

Figure 2. A delegation interface for ground robots performing a building exploration and mapping task.

Neuroergonomics of Individual Differences in Decision Making in BMC[2]

Selection of human operators with highly-developed decision making skills and ability to withstand sustained periods of high workload can be a key to ensuring success on the battlefield. We are following a *neuroergonomic* approach to this problem (Parasuraman, 2003; Parasuraman & Rizzo, 2007; Parasuraman & Wilson, 2008). In our studies, we examined individual differences in decision-making capability under high workload conditions in a simulated battlefield engagement task. Forty subjects were screened for genotypes shown

previously to be linked to high working memory capacity (Parasuraman, Greenwood, Kumar, & Fossella, 2005). Ten individuals were selected for low and high working memory capacity (WMC). Our hypothesis was that high WMC is a key underlying ability in effective decision-making in BMC[2], as evaluated in a simulated "Sensor-to-Shooter" (STS) task performed under conditions of time pressure (Rovira, McGarry, & Parasuraman, 2007).

The STS simulation consisted of three components shown in separate windows: a terrain view, a task window, and a communications module (see Figure 3). The right portion of the screen was dedicated to a two-dimensional terrain view of a simulated battlefield. The window showed red enemy units, yellow friendly battalion units, green friendly artillery units, as well as the blue friendly headquarter unit (HQ). A second window, the task window, was where the user made enemy-friendly engagement selections. The participants were required to identify the most dangerous enemy target and to select a corresponding friendly unit to engage in combat with the target. Subjects were assisted with automation that provided advice on enemy engagement actions. This advice, however, was imperfect, so that operators had to use both their judgment and that of the decision aid in coming to a decision in a timely manner. Automation support was provided on half the trials.

Figures 4 and 5 show the main results. As expected, automation support improved decision accuracy. In addition, individuals with high WMC showed superior decision-making. Furthermore, there was a significant interaction between these two factors. Whereas automation support enhanced performance in low WMC persons, it had no effect in high WMC persons. In other words, individuals with genotypes associated with superior WMC made better and timelier decisions without the need for automation support.

As noted previously, the automation was imperfect. As expected, decision accuracy was relatively good on reliable trials in all individuals. When the automation gave incorrect advice however, many individuals tended to over-rely on the decision aid, so that their decision accuracy suffered. This problem has been noted previously in many human-automation interaction studies (Parasuraman & Riley, 1997).

Sensor to Shooter Simulation with Decision Automation (Recommended Target)
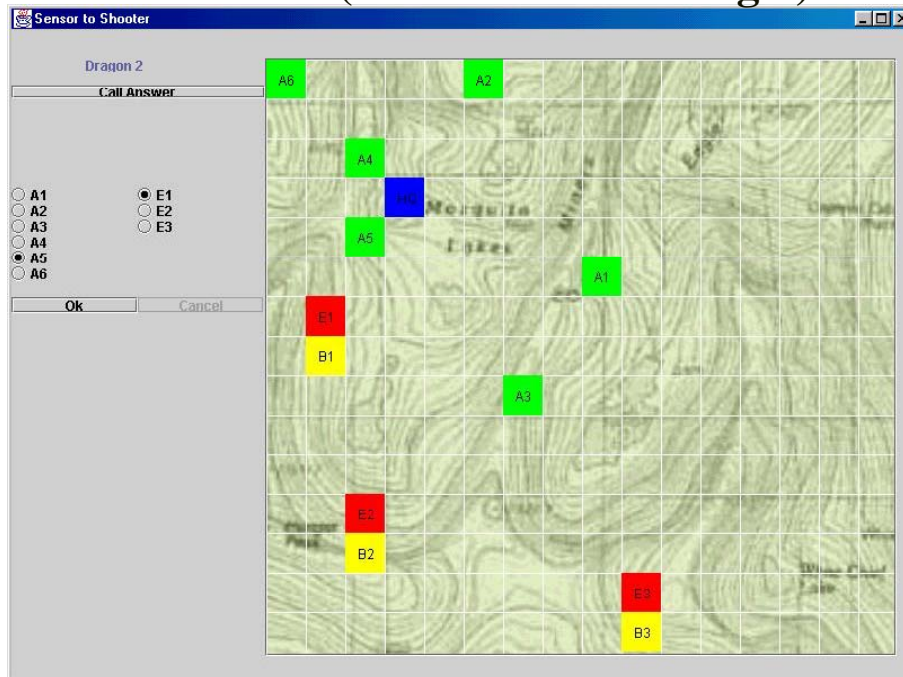

Figure 3. Sensor to Shooter simulation.

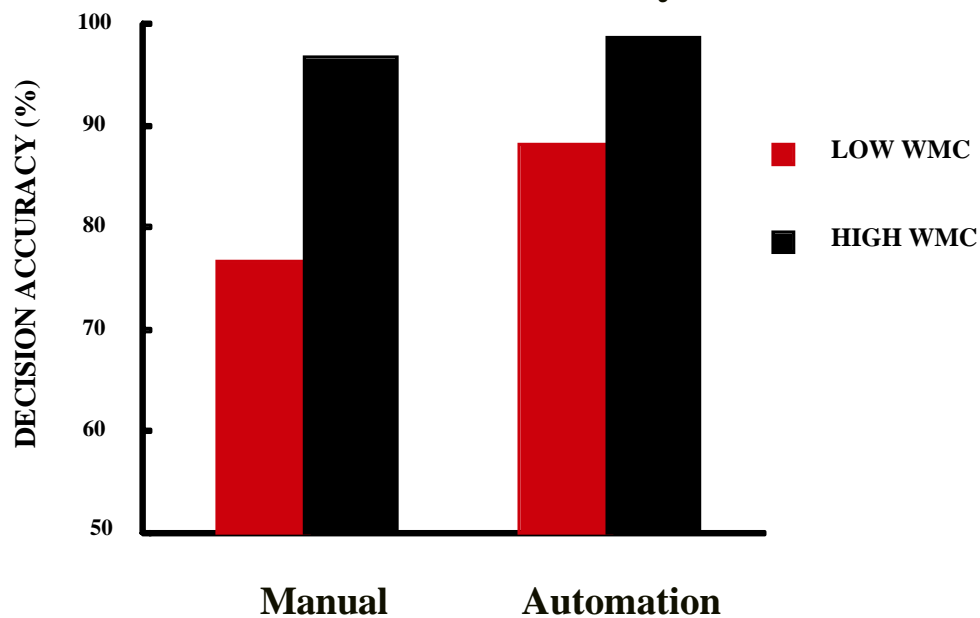# Working Memory Capacity (WMC) and Decision Accuracy

Figure 4. Effects of automation on decision accuracy in low and high WMC persons.

A major finding was that this cost of automation unreliability was significantly reduced in high WMC persons. As Figure 5 shows, both low and high WMC participants were relatively highly accurate in their decisions when supported by reliable automation—at or just below 98%. However, when the automation provided incorrect recommendations for course of action, low WMC individuals were only correct 68% of the time. In contrast, high WMC persons were correct 85% of the time even when the automation was unreliable.

These findings are highly encouraging with respect to the potential for selection of operators for complex decision making tasks in BMC[2]. Selection on the basis of working memory capacity provides a valuable adjunct to adaptive or adaptable automation to the

conundrum of imperfect decision aiding systems. Furthermore, working memory capacity may also provide a basis for individuation of adaptive systems. Figure 5 suggests that adaptive automation may be particularly valuable for individuals with low WMC. This possibility should be explored in future research and development on adaptive systems.

Performance Costs of Unreliable Decision Automation Reduced (But not Eliminated) in high WMC Individuals
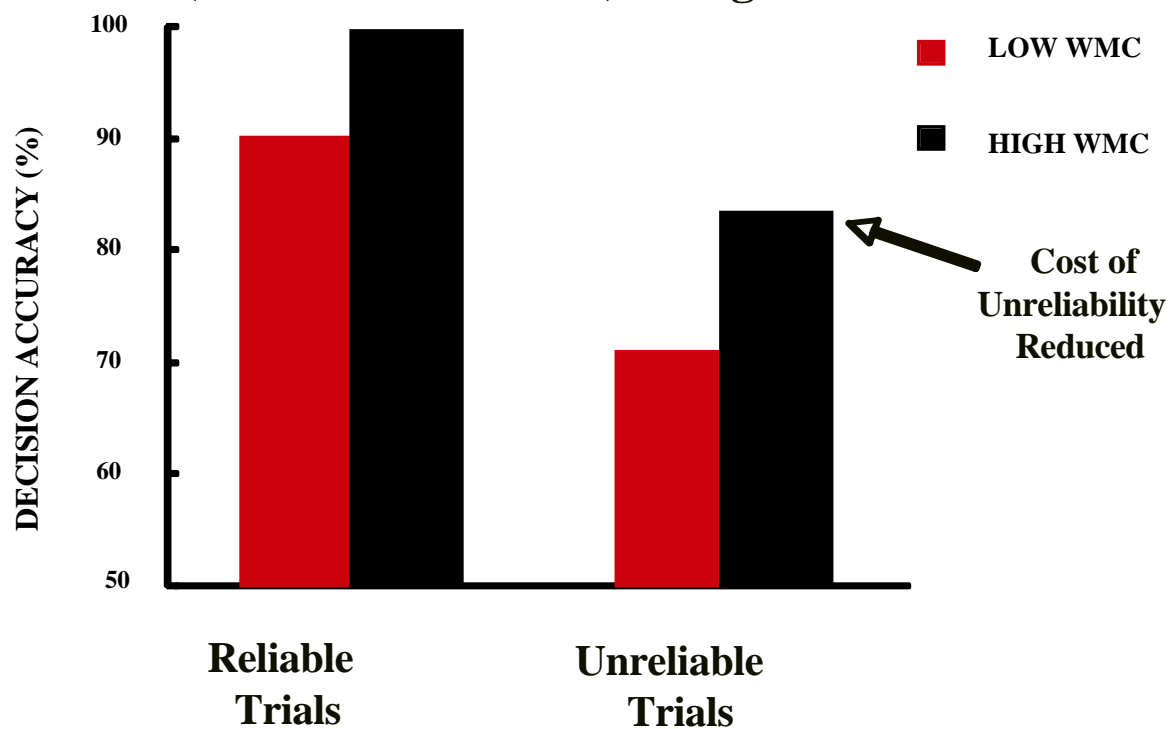
Figure 5. Decision accuracy in reliable and unreliable automation trials in low and high WMC individuals.

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Conclusions

Future combat force structures in Battle Management Command and Control (BMC^2) must be being designed to be capable of flexible response to unpredictable and unconventional adversarial postures. Automated support of operators is mandatory, but automation must be designed to be flexible. We describe a theory of delegation interfaces that allow for such flexibility. Prototype interfaces for human operator supervision of multiple unmanned vehicles are described. The operators of BMC^2 systems must also be appropriately selected and trained for implementing such flexibility.

In addition to supporting human operators with flexible automation, operators of BMC^2 systems must be selected and trained appropriately. We describe how selecting for high working memory capacity can achieve these aims. Selection on the basis of working memory capacity provides a valuable adjunct to adaptive or adaptable automation to the conundrum of imperfect decision aiding systems. Furthermore, working memory capacity may also provide a basis for individuation of adaptive systems.

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